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Evolution Of Fracture Networks In The Upper Oceanic Crust

Final Report for Grant No. N900014-94-J-0313

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Long Term Scientific Objectives

The long term objective of this project was to establish realistic geologic constraints on the variables which contribute to the seismic signal in the upper oceanic crust, and to determine how these variables evolve with age. To begin to address this problem, our short term objective was to characterize the nature of porosity in a section of oceanic crust exposed in the Troodos Ophiolite, Cyprus. By comparing the distribution of volcanic morphologies and their inherent porosity to the distribution of void-filling secondary minerals, we evaluated how porosity created by crustal accretion is modified by alteration as a function of crust ages.

Background

Modification of the abundance and geometry of porosity within volcanic sequences is thought to have a profound impact on the seismic signature of the upper oceanic crust as it ages. The initial porosity structure is dependent upon the type of volcanic morphology such that pillow breccias have higher incipient porosity than pillows, and pillows have higher porosity than flows. Although porosity in the upper oceanic crust may be modified by a variety of processes, the greatest change as a crustal section ages is related to the precipitation of secondary minerals within inter- and intra-lithologic voids. The rates of these mineral reactions are not well constrained; however, relative ages have been determined from depositional sequences and cross-cutting relations in the field, and from radiometric dating.

Approach

To accomplish our scientific objectives, the porosity structure of a section of upper oceanic crust exposed in the Troodos Ophiolite was studied using an integrated field and laboratory approach. The distribution and abundance of porosity was compared to the amount of secondary minerals in order to calculate how porosity created by crustal accretion is modified by alteration as a function of crust ages. Twelve sites were selected that are representative of the range of volcanic morphologies (pillows, massive flows, volcanic breccias) found in modern oceanic crust. The distribution of macroscopic porosity was mapped in the field and fracture maps were analyzed in the laboratory using image analysis techniques. Filled and un-filled fractures and vesicles/vugs were distinguished in order to calculate the change in porosity due to the deposition of secondary minerals. The size, shape, and aspect ratios of different porosity types were determined. Samples of calcite

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were analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in order to place constraints on the age at which the final porosity was achieved.

Accomplishments and Results

Two types of porosity were quantified: macroscopic (macroscopic fractures, vesicles/vugs, \pm interpillow zones) and total (macroscopic fractures, vesicles/vugs, \pm interpillow zones, laboratory-measured microscopic porosity). Our calculations only include porosity associated with distinct volcanic morphologies and do not consider porosity created by tectonic processes. Thus, outcrop-scale porosity measured for the Troodos Ophiolite differs from bulk porosity estimates derived from seismic data and borehole geophysical logs as these approaches incorporate all forms of porosity.

Initial and final porosity values were calculated for all types of porosity. Initial values for fracture, vesicle, and interpillow porosity assumed that all filled and unfilled “voids” were initially filled with seawater. Final porosity is equal to calculated unfilled porosity values. Determination of initial effective porosity values was not as straightforward as for the other types of porosity because the effects of alteration processes are poorly understood. Physical property data for the Troodos volcanics and several DSDP/ODP basement sites show decreasing density with increasing effective porosity. A key question to address is whether this correlation is the result of alteration processes or if alteration is localized where porosity is initially high. Because this question remains unresolved, we used two approaches to determine initial effective values. First, we assumed that progressive alteration results in an increase in effective microporosity and a decrease in density and that the initial effective microporosity was equal to the mean of the samples with the highest density; this is a minimum value. Second, we assumed that effective microporosity was not influenced by alteration processes and that initial and final values are equal; this is a maximum value.

Pillow outcrops have initial macroscopic porosity values from 6 to 17%. The highest values occur close to the paleoseafloor and reflect a greater proportion of interpillow zones, and higher vesicle and interpillow zone porosity. Final macroscopic porosity was lower than initial values, and pillow sites within the seafloor weathering and low-temperature zones show an average decrease of 10-11% and 2-5%, respectively. Total porosity, which includes effective microporosity, was calculated in two ways. Minimum initial total porosity values range from 11 to 21% and maximum initial total porosity values range from 14 to 31%. Although it is likely that neither accurately predicts initial effective porosity, realistic values are probably closer to maximum total effective microporosity values. Final minimum total porosity shows a 1-5% increase at all sites. Final maximum total porosity shows a decrease of 8-10% within the pillows in the seafloor weathering zone and <1-3% in the low-temperature zone. Flow outcrops have initial macroscopic porosity values that range from 6 to 9%; final macroscopic porosity shows a decrease of 2-5%.

The greatest decrease in macroscopic porosity was localized where abyssal hill topography or volcanic edifices and sedimentation rates facilitated the growth of the seafloor weathering zone, which comprises ~10% of the volcanic sequence in the Troodos Ophiolite. Thus in modern ocean basins, alteration would have the greatest effect on crustal porosity in areas of rough topography, where the crests of abyssal hills remain unsedimented for long periods of time. Troodos outcrop and DSDP/ODP core/borehole data show that the porosity of volcanic sequences is spatially heterogeneous due to the combined effects of volcanic morphology and alteration processes and is not simply a function of age. The porosity structure of old oceanic crust may be vertically zoned where variable seafloor topography and low-sedimentation rates allow for the development of the seafloor weathering zone. Although the new Troodos data provide some support for the models that predict that changes in the seismic signal with age reflect a reduction in porosity

and the nature of the void-filling materials, the evolution of the upper oceanic crust cannot be uniquely described by seismic data.

The results of this study are published in the Journal of Geophysical Research:
K.M. Gillis and K. Sapp, 1997, Distribution of porosity in a section of upper oceanic crust exposed in the Troodos Ophiolite, *Journal of Geophysical Research*, 102, 10,133-10,150.

Impact on Science

This study provides important, new data for modeling how the seismic signal is impacted by the geometry of volcanic morphologies and alteration processes.